Supplementary Information

Methods

Determining the plantation boundaries

The study area polygons were not provided in a data repository or shared upon request. We therefore digitized the boundaries of the study area ourselves based on Figure 5 in Zachlod et al. [1], which showed locations and types of analysed mills and oil palm plantations in Sabah, Malaysia.

The digitization work involved taking multiple screenshots of the study area from Figure 5 of Zachlod et al. [1] and the concession data from Nusantara Atlas: https://map.nusantara-atlas.org/), where we converted them to JPEG format and used these images as a backdrop for on-screen digitizing in ArcGIS. We also used available RSPO certified concession data from the GeoRSPO Portal https://rspo.org/as-an-organisation/tools/georspo/ to verify whether any matching oil palm boundaries were present in Figure 5 of Zachlod et al. [1]. One limitation encountered during digitization was the challenge of accurately mapping smaller area boundaries, which were often unclear or poorly defined in Figure 5 of Zachlod et al. [1].

Detection of oil palm replanting with Random Forest

We applied two complementary methods to assess whether recent replanting explains the canopy cover declines reported by Zachlod et al. [1]. Oil palm replanting typically occurs every 25 years due to declining yields from aging palms. During replanting, mature trees are cleared and replaced (Figure S1), resulting in temporary canopy loss observable in satellite imagery (Fig. S2: Oil palm development stages. Left: Sub-metre resolution imagery (Google Earth © Google) illustrating four growth stages (1–4). Right: PlanetScope time series (June 2018–January 2021) with orange highlights and cyan plantation boundaries from Zachlod et al. (2025).)

For the first approach, we used a Random Forest classification on Landsat time series to detect bare land within certified plantations for 2016-2024. Bare land identified within oil palm plantations corresponds to areas cleared for replanting. The second approach was based on the estimation of oil palm planting years using the method described in Descals et al. [2].

Figure S1. Oil palm replanting in progress in a plantation on Belitung Island, Indonesia. Photo by Erik Meijaard

The first approach is a replication of the land cover classification used by Zachlod et al. [1] but with methodological improvements. First, we classified a dense time series of Landsat imagery for all years between 2016–2024, not just annual composites for years 2018, 2020, and 2023. We classified each Landsat-7, -8, and -9 scene independently using the Random Forest model from Descals et al. [2]. The classification layers were then aggregated into annual land cover maps for each year between 2016 and 2024. In the aggregation, we prioritized bare land to reflect replanting dynamics; if any Landsat observation within a given year indicated bare land at a pixel, we labelled that pixel as bare land in the annual classification. This rule captures the transient clearing associated with replanting and avoids mislabelling rapidly replanted areas as permanently vegetated. Using the annual classification layers, we estimated the total oil palm coverage for each year from 2016 to 2024 and evaluated any potential trends. In addition, we quantified the total area under replanting for the 2016–2024 period. This was done by counting the area where any pixel in the annual classification layer was classified as bare land.

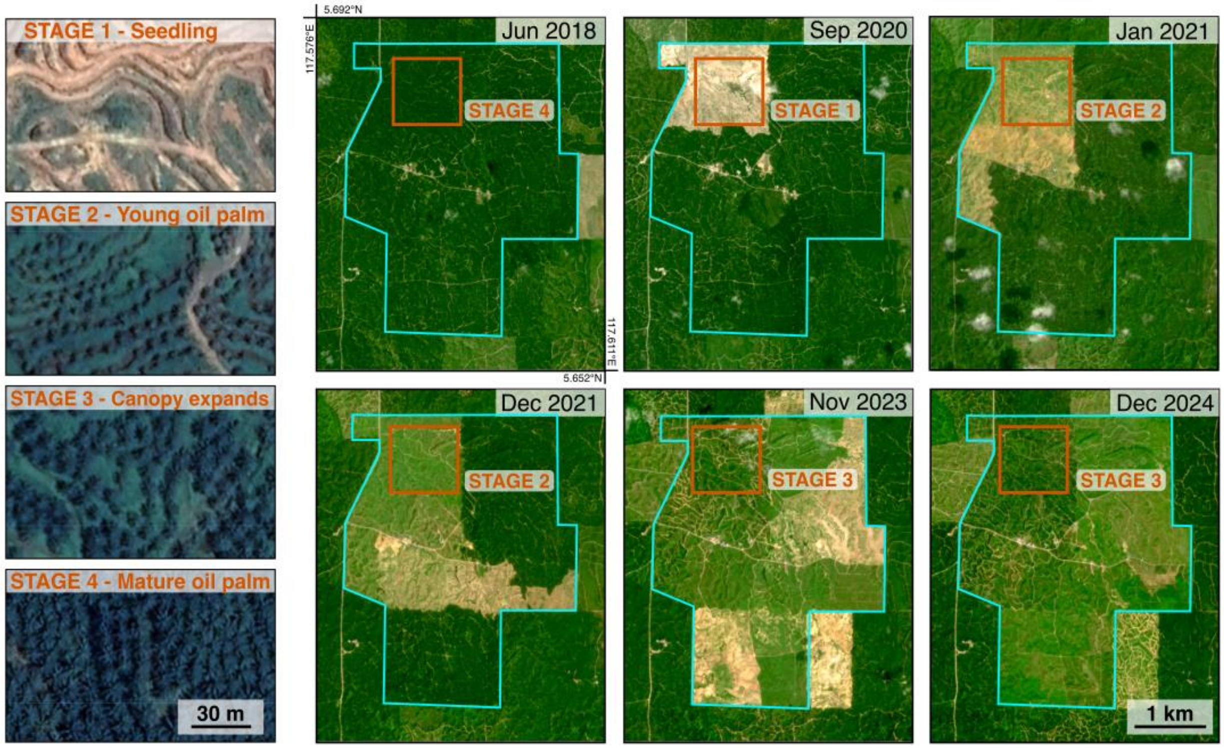

Fig. S2: Oil palm development stages. Left: Sub-metre resolution imagery (Google Earth © Google) illustrating four growth stages (1–4). Right: PlanetScope time series (June 2018–January 2021) with orange highlights and cyan plantation boundaries from Zachlod et al. (2025).

Estimation of oil palm age

The second approach estimated oil palm planting year as described in Descals et al. [2]. This method also uses the same random forest model to classify the Landsat time series, but the aim is to detect the planting year. First, the Landsat time series is classified into bare land and vegetation from 1984 to 2023. The method extracts the last date classified as bare land, which indicates the final stage of land preparation prior to replanting. We call this observation the last bare land date. We then estimated the planting year as the year with the lowest Normalized Difference Water Index

(NDWI) within the five years preceding the LBLD. This approach has been validated with in situ data from industrial and smallholder plantations [2]. Applying this method across all certified plantations allowed us to map the distribution of oil palm age and identify areas with recent planting or replanting.

The trends in oil palm coverage, area under replanting, and planting year were estimated for two groups: RSPO-certified and non-certified plantations. The RSPO-certified group includes the plantations considered in Zachlod et al. [1]. The non-certified plantations served as a control group to evaluate if RSPO certification may play a role in the replanting status and oil palm coverage within the study period. The non-certified plantations contain areas classified as oil palm during 2016-2024 using Descals et al. [2] that are not considered RSPO plantations according to GeoRSPO dataset [3]. The non-certified plantations were selected within the 100x100 km tiles, defined in Descals et al. [2], that cover all the certified plantations in Zachlod et al. [1].

References

1 Zachlod, N., Hudecheck, M., Sirén, C. & George, G. Sustainable palm oil certification inadvertently affects production efficiency in Malaysia. *Communications Earth & Environment* **6**, 200, doi:10.1038/s43247-025-02150-2 (2025).

2 Descals, A., Gaveau, D. L. A., Serge, W., Szantoi, Z. & Meijaard, E. Global mapping of oil palm plantation age for 2021. *Earth System Science Data*, doi: 10.5194/essd-16-5111-2024 (2024).

3 RSPO. GeoRSPO. https://rspo.org/as-an-organisation/tools/georspo/. Accessed on 14 November 2025. (2025).